Proceedings of the 9th International Conference on Photoacoustic and Photothermal Phenomena, June 27-30, 1996, Nanjing, P.R. China

Laser ultrasonic monitoring of molten metal processes

K. L. Telschow and J. B. Walter
Idaho National Engineering Laboratory, Idaho Falls, ID 83415, U.S.A.

R. J. Conant and S. E. Garwick
Montana State University, Bozeman, MT 59717, U.S.A.

ABSTRACT

The noncontacting nature of laser-based ultrasonic measurement has made it attractive in many high temperature materials processing applications. Locating and characterizing the shape of the solidification front is of prime importance for the metal casting and refining industries. Since the laser ultrasonic approach requires only optical access to the free surface, it is well suited to molten metals, where immersion of the measurement probe is often not desired. This paper describes the results of an investigation of the information obtainable with laser ultrasonic methods using several different molten metals.

LASER ULTRASONIC GENERATION EFFICIENCY IN MERCURY

There are two modes of ultrasound generation for a pulsed laser incident on the surface of a liquid metal, thermoelastic expansion and ablation. Thermoelastic generation has been investigated both theoretically[1] and experimentally[2]. It results in acoustic dipole radiation due to the free surface boundary. The ablative source acts as a point force on the liquid surface and also produces acoustic dipole radiation. Both sources lead to the same far field intensity pattern; exhibiting diffraction similar to that from conventional piezoelectric transducers. However, it has been found that the ablation source is far more efficient at ultrasound generation than the thermoelastic.

Mercury is a simple material with which to study the laser generation mechanism in molten metals since it is liquid at room temperature. Ultrasonic wave amplitudes in the far field as a function of pulsed laser energy (Nd:YAG) are shown in Figure 1. The laser source was incident on the liquid surface. The ultrasonic wave amplitude was measured by two methods: (1) an immersed small piezoelectric transducer, 10 MHz pinducer and (2) optically, by the use of the Fabry-Perot interferometer at a radial distance of about 2 cm from the source point along the inside surface of a cylindrical glass container. A rapid increase of the ultrasonic amplitude, determined from the signal energy, with

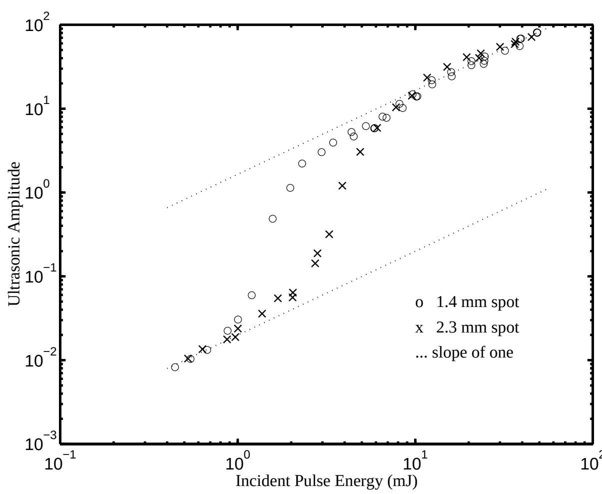

Figure 1. Laser generated ultrasonic wave amplitudes in mercury for two laser spot sizes.

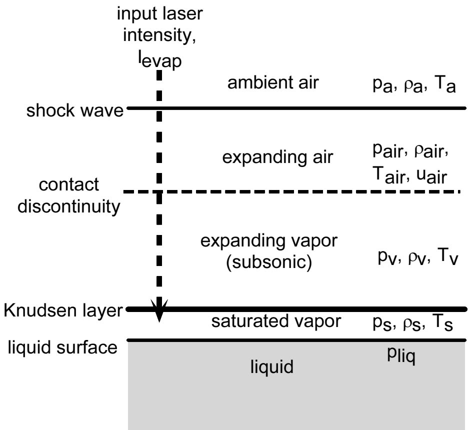

Figure 2. Model for the ablation process occurring at the liquid surface.

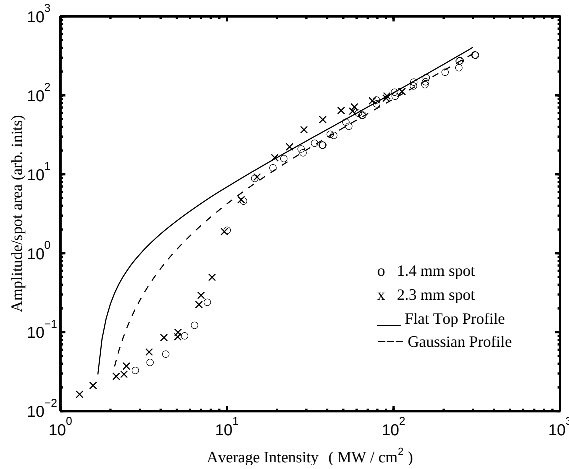

Figure 3. Ultrasonic amplitudes for laser generation in mercury normalized by the incident beam area.

laser intensity in the transition region between thermoelastic and ablation source mechanisms is seen. The incident pulse energy, up to an apparent threshold energy density, heats the liquid to the point of vaporization, producing ultrasound by thermoelastic expansion. Absorbed energy beyond the threshold ejects material from the pool, producing ultrasound by ablation. For mercury, ablation produces about 100 times larger ultrasonic pulse amplitudes than thermoelastic expansion and has a threshold of about 6 MW/cm^2, designated as the point where the ablation component begins to dominate the thermoelastic component.

A model for laser ablation has been developed incorporating the shock wave that develops during ablation as well as a Knudsen layer adjacent to the liquid-vapor interface[3,4]. The model, applied to laser ultrasonic generation and shown in figure 2, accounts for subsonic and, with the addition of an additional region describing the limiting behavior of the Knudsen layer, supersonic flow above the liquid surface[5]. It predicts that a significant transient pressure is generated at the liquid surface when ablation occurs and describes the ablation process in a continuous manner starting from the boiling temperature. Incident laser pulse energy is divided first into heating the liquid up to the boiling point, which acts as the ablation threshold, and then into the ablation process. Experimentally, the appearance of a threshold is due to the very rapid rise of saturated vapor pressure with temperature as the boiling point is approached, this model assumes no evaporation occurs before the boiling temperature is reached. The acoustic pressure results from compression behind the shock wave and from the recoil momentum of the vapor as it leaves the interface. The recoil momentum pressure component is large compared to its thermoelastic counterpart once temperatures near the boiling temperature are reached. By utilizing the jump conditions across the Knudsen layer and the shock front, the results show that the acoustic pressure just below the liquid surface is approximately proportional to the laser pulse energy that is absorbed and directed into the ablation mechanism. This conclusion is supported by the experimentally measured results of figure 3 in the ablation region. The expanding vapor, even at subsonic velocities, causes the air flow above it to reach a mach number greater than one, generating the shock front. Higher irradiation intensities cause supersonic flow in the vapor region and larger shock amplitudes in the air region. Alternate materials exhibit different ablation efficiencies due to their different densities and enthalpies at the high temperatures reached during ablation. Molten metal surfaces can easily heal any deformation due to ablation, thereby presenting a nearly ideal material with which to investigate

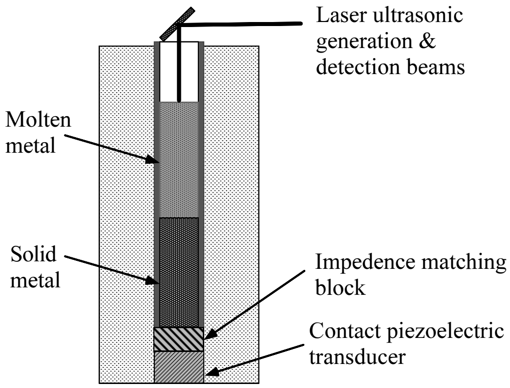

Figure 4. Vertical tube furnace for solidification front location in tin.

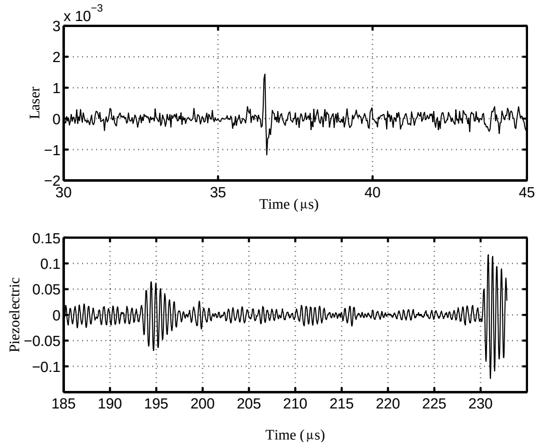

Figure 5. Solidification front echo in tin by the laser (top) & piezoelectric (bottom) methods.

the ablation mechanism for ultrasound generation. Further developments will account for the evaporation occurring during the approach to the boiling temperature.

SOLIDIFICATION FRONT DETECTION

Solidification front location and shapes were investigated by ultrasonic reflection, first in a low melting point metal, tin. A vertical tube furnace was used to maintain tin in both liquid and solid phases simultaneously[6]. Both the pulsed laser generation beam and the detection beam were focused on the liquid surface as shown in figure 4. The ultrasonic wave, generated at the surface, traveled down to the solidification front, reflected, and was detected at the liquid surface a small distance away from the source beam. In addition, a piezoelectric transducer was used to generate ultrasonic waves at the bottom of the furnace that traveled up through the impedance matching block and into the solid tin. These waves reflected from the solidification front and also from the liquid surface and were detected by the same piezoelectric transducer. Waveforms showing the solidification front echo are displayed in Figure 5. The laser method is wideband, producing a narrow echo signal pulse, whereas the piezoelectric method is essentially narrowband, producing a signal characteristic of transducer ringing. The laser results are also free of spurious signals from internal reflections in the impedance matching block such as are present in the piezoelectric recorded waveforms.

The location of the solidification front, over depths greater than 10 cm, was altered by changing the temperature gradient along the tin column. The echo signals are shown in figure 6 and were found to be dependent on the solidification front shape. As the heat flow was altered, a flat solidification front surface was not always established.

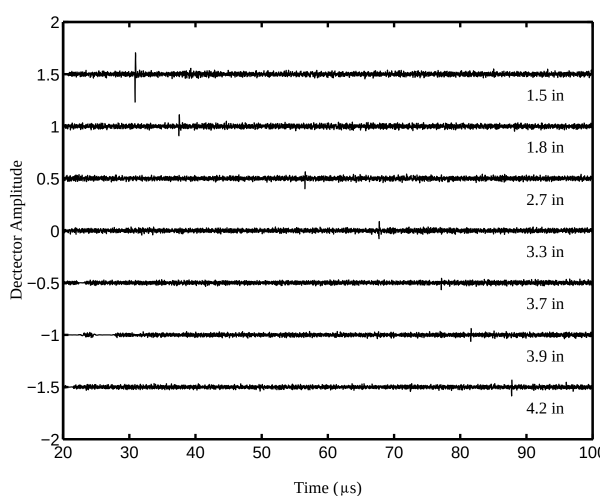

Figure 6. Solidification front echoes in tin recorded for different molten metal depths.

The front was made more planar, increasing the reflection signal amplitude, by holding the temperature gradients constant. Front motions of as small as 1 mm/min resulted in significantly reduced echo amplitudes. Alloy solidification fronts were investigated by adding lead, 0.6%, to produce an 8-12 mm mushy zone that resulted in reflection signal amplitudes near the detection limit.

HIGH TEMPERATURE MOLTEN METAL MEASUREMENTS

Currently, work is underway applying laser ultrasonic methods to molten metals at very high temperatures, greater than 1600 °C. These temperatures allow measurement on many industrial materials. Figure 7 shows the measurement geometry for plasma arc heating. Since the generation laser is of such high intensity, typically 10-100 MW/cm^2, high temperatures, as are needed for the melting of industrial materials, are not an obstacle to the laser method as long as both the generation and detection laser beams can reach the molten surface and the detection beam can be captured outside the chamber. Experience has shown that even though attenuation is markedly increased at high temperature, depths of 1-2 inches can be easily investigated in molten industrial metals with potentially greater depth measurement possible using adequate laser powers. Laser ultrasonics shows great potential for studying the properties of solidification in metals, where the solidification front location, structure, and growth rate all affect the signals measured. This work was sponsored by the U.S. Department of Energy, Office of Defense Programs, under DOE Idaho Operations Office Contract DE-AC07-94ID13223 and the Montana State University's Engineering Experiment Station through its RSPE program.

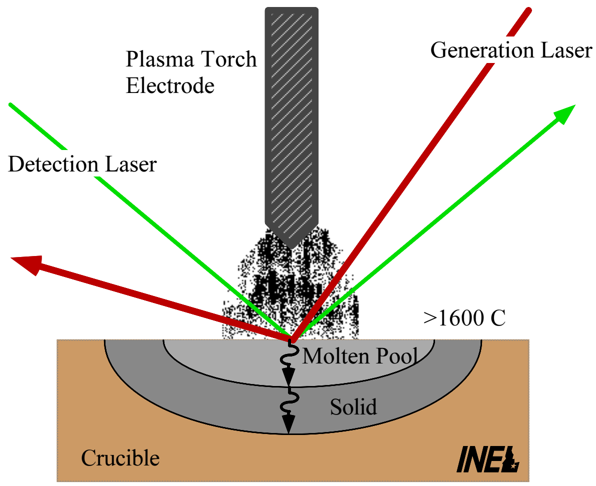

Figure 7. Geometry for laser ultrasonic measurements directly beneath a plasma arc electrode for investigation of very high temperature melting metals.

[1] F.V.Bunkin, A.A.Kolomensky and V.G.Mikalovich, Lasers in Acoustics, (Harwood Publishers, Philadelphia, PA, 1991)

[2] J.B. Walter, K.L. Telschow, and R. J. Conant, "Laser Ultrasonic Generation at the Surface of a Liquid Metal", Review of Progress in Quantitative NDE, Vol. 14 edited by D.O. Thompson and D.E.Chimenti (Plenum Press, New York, 1995)507-512.

[3] C. J. Knight, "Theoretical Modeling of Rapid Surface Vaporization with Back Pressure", AIAA J. 17, 519 (1979).

[4] A. D. Zweig, "A Thermo-mechanical Model for Laser Ablation", J. Appl. Phys. 70(3), 1684 (1991).

[5] R. J. Conant and S. Garwick, "Mathematical Modeling of Laser Ablation in Liquids with Application to Laser Ultrasonics", Review of Progress in Quantitative NDE, Vol. 16 edited by D.O. Thompson and D.E.Chimenti (Plenum Press, New York, 1996) to be published.

[6] J. B. Walter and K. L. Telschow, "Laser Ultrasonic Detection of the Solidification Front During Casting", Reviews of Progress in Quantitative NDE, Vol. 15A edited by D. O. Thompson and D.E.Chimenti (Plenum Press, New York, 1996) 607-613.